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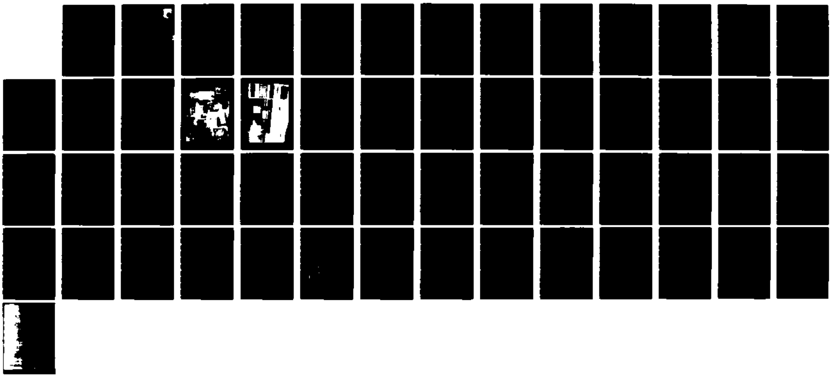

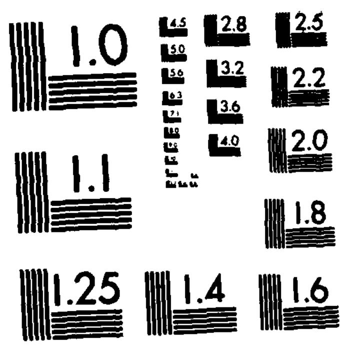

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LUBRICANT EVALUATIONS OBTAINED USING THE AUTOMATED AFAPL ENGINE SIMULATOR

SOUTHWEST RESEARCH INSTITUTE
6220 CULEBRA ROAD
SAN ANTONIO, TEXAS 78284

JANUARY 1983

FINAL REPORT FOR PERIOD 20 APRIL 1981 - 20 SEPTEMBER 1982

AERO PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
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This technical report has been reviewed and is approved for publication.

Leon J. DeBrohun

LEON J. DEBROHUN
Project Engineer
Lubrication Branch

Howard F. Jones

HOWARD F. JONES, Chief
Lubrication Branch
Fuels and Lubrication Division

FOR THE COMMANDER

Robert D. Sherrill

ROBERT D. SHERRILL, Chief
Fuels and Lubrication Division
Aero Propulsion Laboratory

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A description of an automated gas turbine engine simulator, designated the AFAPL engine simulator, and a discussion of the test results obtained from 31 tests using the simulator are presented. The No. 4-5 bearing compartment areas of a J57 turbine engine are used as the basic hardware for the simulator. The simulator is driven by a variable-speed drive

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20. ABSTRACT (CONT'D)

system, through the accessory drive gearbox, providing simulator mainshaft speeds up to 9,120 rpm. Electrical resistance heaters are used to heat the air surrounding the oil-wetted areas within the No. 4-5 bearing compartment areas. The temperatures, pressures, and rpm are controlled at predetermined levels and monitored throughout the 9120-6000 rpm speed cycling sequences and the soakback periods by a Hewlett-Packard mini-computer system, which is also programmed to draw 5-hr interval test-oil samples, control test-oil sump level, provide safety shut-off protection, as well as print out and plot test information generated during each individual test. Simulator results obtained on eight turbine engine lubricants, for which full-scale engine data are available, show a very good correlation of the deposit ratings obtained using the AFAPL engine simulator and the deposit ratings from full-scale engine tests.

PREFACE

This technical report was prepared by the Mobile Energy Division of Southwest Research Institute (SwRI). The effort was sponsored by the Aero Propulsion Laboratory (APL), Air Force Wright Aeronautical Laboratories (AFWAL), Air Force Systems Command, Wright-Patterson AFB, Ohio under Contract No. F33615-78-C-2012 for the period 20 April 1981 to 20 September 1982. The work herein was accomplished under Project 3048, Task 304806, Work Unit No. 30480657, "Turbine Engine Lubricant Simulator Parameters," with Mr. L.J. DeBrohun, AFWAL/POSL, as Project Engineer. Mr. B.B. Baber of Southwest Research Institute was technically responsible for the work. The technical contributions of J.A. Pasquali and J.E. Wallace of Southwest Research Institute are acknowledged.

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INTRODUCTION

General

This report summarizes the work performed at Southwest Research Institute (SwRI) during the period of April 20, 1982 through September 20, 1982 on a program concerned with further utilization of the AFAPL engine simulator in determining the lubricant deposition and degradation characteristics of selected aircraft turbine engine lubricants.

Realizing the large expenditures of time and money necessary to obtain sufficient full-scale engine data, the Aero Propulsion Laboratory (APL) contracted with SwRI in 1972 (Contract No. F33615-72-C-1097) to develop an engine simulator test that would minimize the need for conducting full-scale engine tests to determine the deposition and degradation characteristics of lubricants. As a result of the contract, the AFAPL engine simulator was designed and developed(1)* by SwRI. Deposition results from the AFAPL engine simulator using eight turbine engine lubricants for which full-scale J57-29 engine data were available, showed a very good correlation of the deposit ratings obtained using the AFAPL engine simulator and the deposit ratings obtained from the No. 4-5 bearing compartment areas from the full-scale engine tests conducted at APL.

The AFAPL engine simulator was further refined under AF Contract F3361578-C-2012 by automating the operation, control, and data management systems of the simulator during test(2) such that the normal operating technician time required to run a simulator test would be reduced.

A quick comparison of the costs for power to operate the AFAPL engine simulator versus fuel costs to operate the APL full-scale J57 engine test indicates that the engine simulator costs approximately $600 for electrical

*Superscript numbers in parentheses refer to the List of References included in this report.

power during a 100-hr test, while the APL full-scale engine requires over $100,000 for fuel to operate for 100 hr. Since the APL full-scale engine test remains as the final "pass" or "fail" criterion for candidate turbine engine lubricants, considerable savings in fuel costs, not to mention the conservation of fuel, can be realized by using the engine simulator as the last screening tool prior to full-scale engine testing.

The J57 turbojet is a continuous flow gas turbine engine employing a multistage reaction turbine to drive a two-spool multistage axial flow compressor. This basic engine is used in numerous military aircraft. Due to the relatively large population density of this engine in the Air Force inventory, it was selected by APL for use in all full-scale engine tests conducted by APL. In addition, the No. 4-5 bearing compartment areas of the J57 engine were subsequently selected as the basic hardware for the AFAPL engine simulator. This area of the J57 engine is considered to be the most critical with respect to lubricant depositon and degradation due to the normally high temperatures surrounding the oil wetted areas of the No. 4-5 bearing compartment.

The simulator operates in the horizontal position and is driven by a variable-speed drive system which provides compressor shaft speeds up to 9,120 rpm. Filtered air is introduced into the No. 4 compartment and directed over finned air heaters. As in the full-scale engine, a portion of the incoming air passes through the conical section to the No. 5 compartment. The combined seal leakage of the Nos. 4 and 5 seals passes through the breather tube strut and is directed to a trap, demister, and precipitator. Electrical resistance heaters are used to heat the air in the No. 4 and 5 bearing-seal areas to realistic operating temperatures. In addition, electrical resistance heaters are used to provide additional heat, as required to the No. 4 bearing housing, the conical section, and the breather strut.

An external test oil system provides lubricant to the simulator at the normal operating engine oil pressure. Approximately two-thirds of the test oil flow is provided to the internal oil system of the simulator. The remaining oil flow is jetted into the front and rear of the accessory drive gearbox to provide additional cooling to the gearbox. A heat exchanger is used to cool the oil flow to the gearbox. Additional heat exchangers are used in the simulator and gearbox oil return lines to the external sump.

The simulator test sequence is patterned after the cycling test procedure (25 min operation at 9120 rpm, followed by 6000 rpm operation for 5 min) used at APL for the full-scale engine test. A 1-hr soakback period (not counted as part of the test time) is performed after each 2.5 hr of test cycling. This 2.5 hr test cycle is repeated 40 times to complete a 100-hr simulator test.

Temperatures, pressures, and rpm are automatically controlled at predetermined levels and monitored throughout the speed cycling sequences and the soakback periods by a mini-computer system having a 64K semiconductor core memory. This computer system, used in conjunction with appropriate electronic interface devices, a CRT with keyboard, an X-Y plotter, a line printer, and associated software programs provides for the automated operation of the simulator; extensive protection control and test rig shut-off limits for the various temperatures, pressures, etc. monitored; automatic sampling of the test oil each 5 hr; automatic measurement of the demister and precipitator fluid and its return to the sump; and automatic test-oil sump level control. The data from 63 sensors (temperature, pressure, rpm) are automatically monitored, averaged, and stored for the 9120 rpm and 6000 rpm speed cycles and later printed out to provide a section of the final test report. Temperature information from selected areas of the simulator are also monitored, averaged, and stored, for the 1-hr soakback periods. Average soakback temperature curves are generated by the X-Y plotter following each test. In addition, other information such as test-oil viscosity, neutralization number, and iron

content; and, the numerical values of the visual inspection of the deposits of selected oil-wetted engine parts are manually input into the computer and then are used to compute and print out programmed information required for the test report.

Summary

This report presents a summary of all of the test data generated to date on APL submitted lubricants using the AFAPL engine simulator. The data presented here were obtained during the following AF contracts: F33615-72-C-1097, F33615-78-C-2012, F33615-81-C-2005, and F33601-81-C-0398. Individual test reports have been submitted to APL following the completion of each engine simulator test.

A total of 31 AFAPL engine simulator tests have been conducted, accumulating over 4,300 test hours on the simulator, while conducting evaluations on 24 turbine engine lubricants. Eight of the lubricants evaluated in the engine simulator have been previously evaluated in the APL full-scale engine test. A comparison of the numerical deposit ratings obtained from the No. 4-5 area of the full-scale engine shows good correlation, with a calculated correlation coefficient of 87.4 percent.

TEST EQUIPMENT AND PROCEDURES

General

Detailed descriptions of each of the AFAPL engine simulator operating systems have been presented earlier[2] and will not be repeated here. However, sufficient information is included herein on the various operating systems and procedures to afford a general understanding of the engine simulator operation.

Test Equipment

AFAPL Engine Simulator. The AFAPL engine simulator was designed to provide a relatively simple but flexible test facility with the capability of closely simulating the critical temperatures and oil flow variables experienced by the lubricant in the full-scale engine. Figure 1 illustrates the No. 4-5 bearing compartment areas of the J57-43 engine used as the heart of the simulator. The simulator is driven through the accessory gearbox by a variable-speed drive system providing simulator speed capabilities up to approximately 9,120 rpm. A maximum design temperature of 800°F (427°C) for the heated air in the No. 4 compartment and 850°F (454°C) in the No. 5 compartment is provided by finned electrical resistance heaters. The No. 4 bearing housing and the conical section are heated by band type electrical resistance heaters while the breather tube strut is heated by an open wire electrical resistance heater.

It will be noted in Figure 1 that the low pressure compressor drive rotor and the No. 4-1/2 bearing are not included in the simulator. Since these parts are not included, modifications were required to some of the standard hardware parts. For example, 4 holes in the rear shaft, normally used as return oil passages from the No. 4-1/2 bearing, were welded closed in order to provide a sealable air system within the simulator. In addition, the hub and rear shaft were modified to remove excessive weight

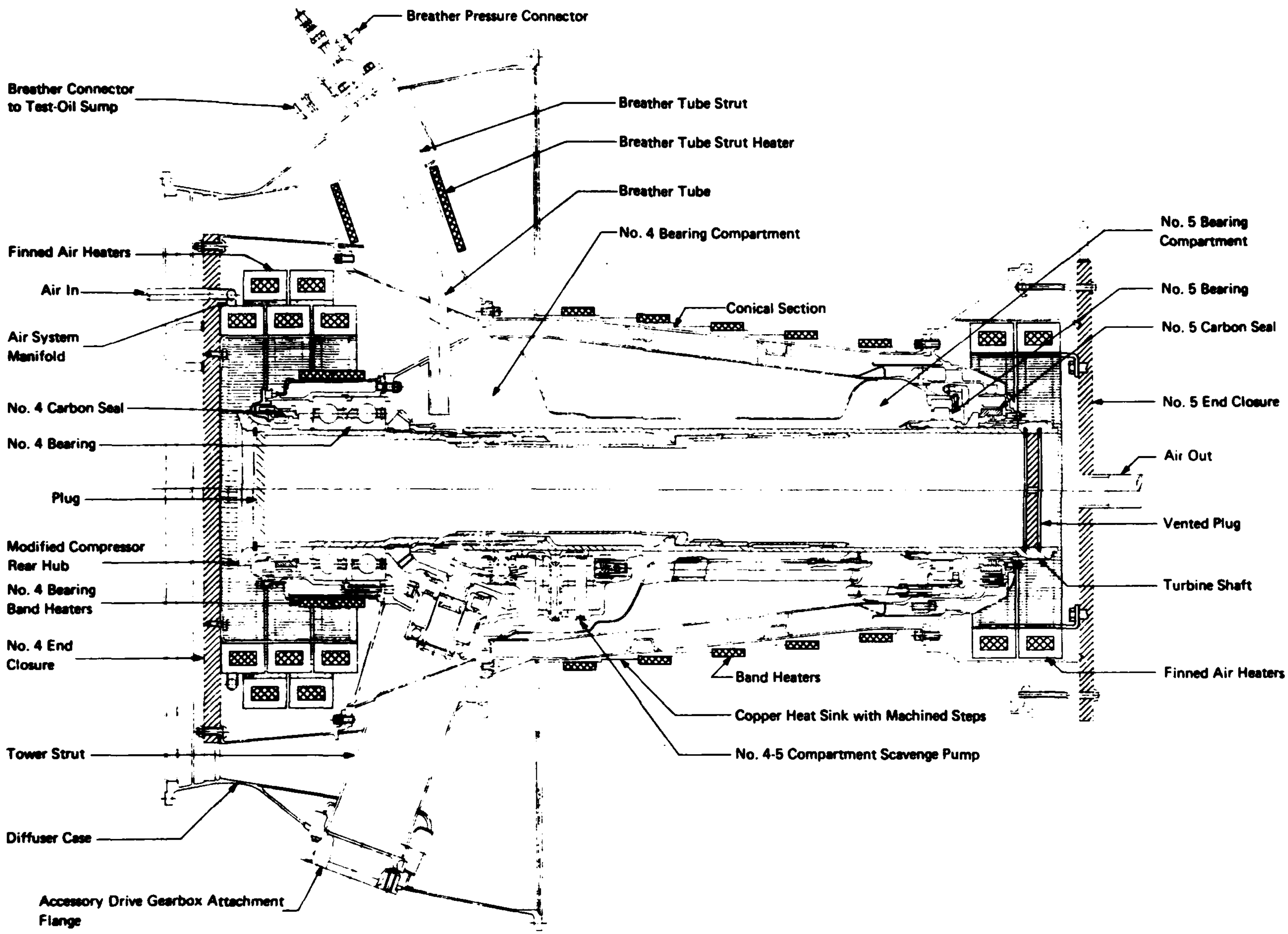

FIGURE 1. CROSS SECTION OF AFAPL ENGINE SIMULATOR

and to allow additional room for air heaters. Plugs were incorporated into the ends of the hub and rear shaft to minimize air flow through the shaft and thereby provide the same air flow paths as those in the full-scale engine. Following the modifications to the hub and rear shaft, the complete rotating assembly was dynamically balanced. The No. 4 bearings are normally thrust loaded in the engine due to forces from the turbine section. In the simulator, the No. 4 bearings are preloaded during assembly to prevent the possibility of ball skidding during operation. The bearing preload is accomplished by changing the thickness of one of the bearing spacers. End closures were provided for the No. 4 and 5 compartment areas to provide a pressure tight system and to provide attachment points for the finned air heaters.

Figure 2 presents a view of the AFAPL engine simulator with the external test-oil system, including the automated test-oil sampling system, the demister, precipitator, and pour-back sump, shown on the right.

Computer Control System. The automated AFAPL engine simulator control console is shown in Figure 3. The simulator is controlled by a Model 40 Hewlett-Packard (H-P) 1000E, Series 2113, General Purpose Disc Based Mini-Computer System, including a 2648A graphics terminal, a 7900A disc (5M byte), an RTE-II-III real time driver, a 7245A printer/plotter, and a 2635A printing terminal. This computer system, used in conjunction with appropriate interface devices, sensors, and software programs provides for the automated operation of the simulator. In order to obtain automated operation of the simulator, 12 separate process loops must be controlled, and five on-off type controls are reset periodically, based upon time. In addition to extensive protection control and shut-off limits for the various temperatures, pressures, etc. monitored for safety, information from 63 sensors (temperature, pressure, rpm) are automatically monitored, stored, and averaged for the 9120 rpm and 6000 rpm speed cycles and later printed out to provide a section of the final test report. Temperature information from selected areas of the simulator are also monitored, stored, and averaged for the 1-hr soakback periods. Average soakback

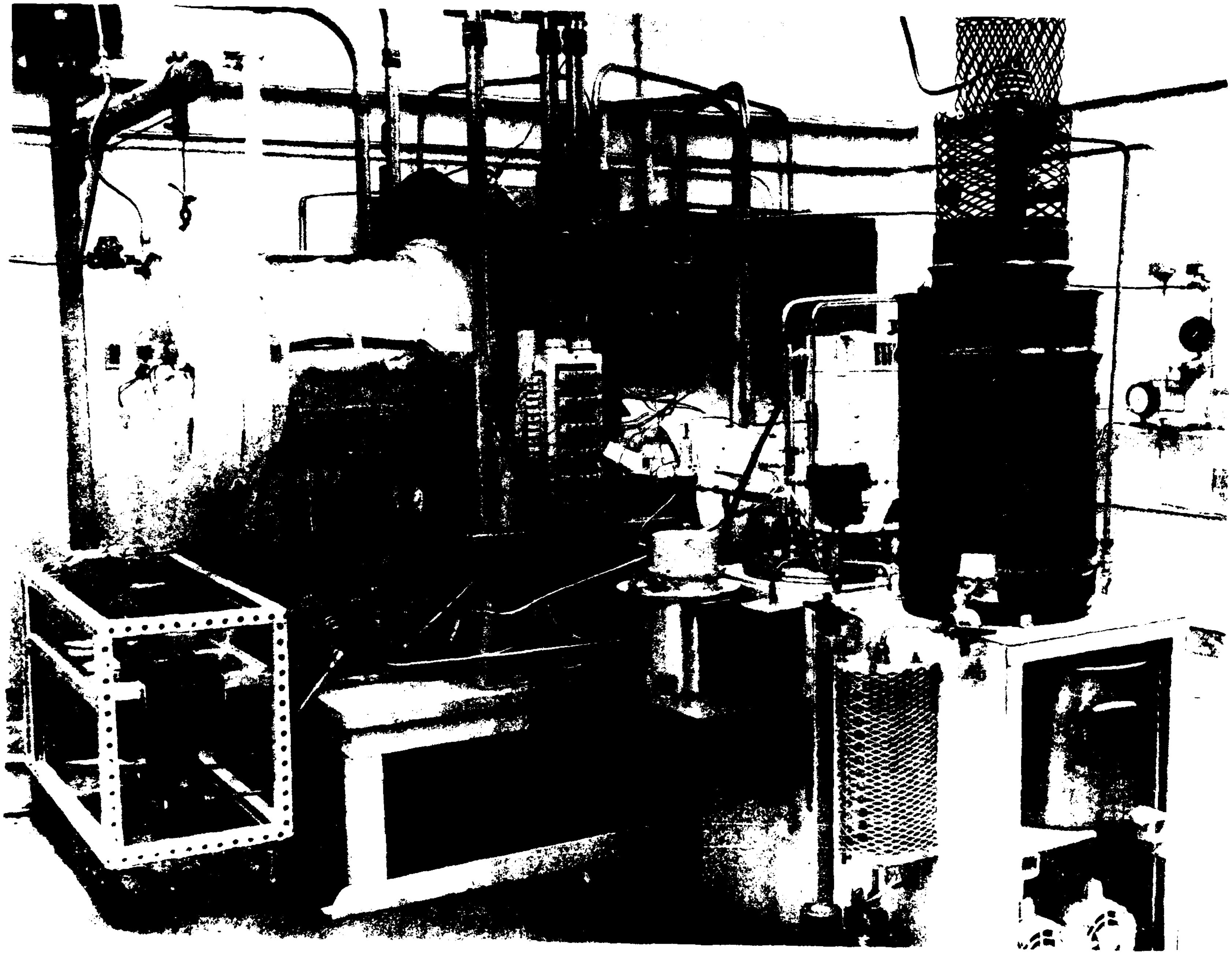

FIGURE 2. AFAPL ENGINE SIMULATOR WITH EXTERNAL TEST OIL SYSTEM

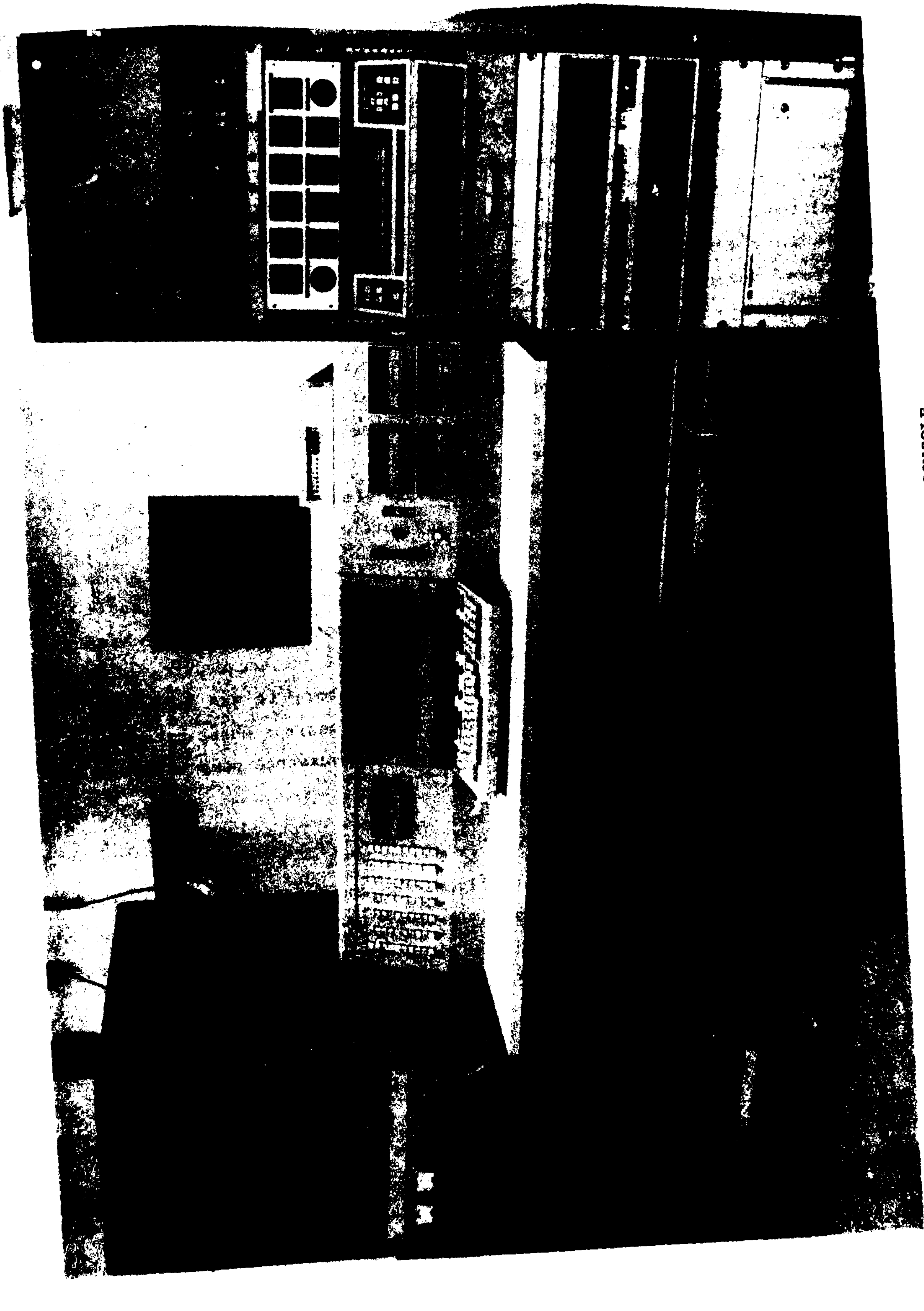

FIGURE 3. AFAPL ENGINE SIMULATOR CONTROL CONSOLE

temperature curves are generated by an X-Y plotter following each test. In addition, other information such as test-oil viscosity, neutralization number, and iron content; and, the numerical values of the visual inspection of the deposits of selected oil-wetted engine parts are manually input into the computer and then are used to compute and print out programmed information required for the test report.

Drive System. The simulator is driven by two 50-hp (37.3kw) variable speed Dynamatic drive units coupled through timing belts to the accessory drive gearbox extension shaft. This drive system provides an infinitely variable speed range up to approximately 9,120 rpm for the simulator main shaft assembly, and allows the simulator to be slowly accelerated to the maximum operating speed without damaging any portion of the drive system.

In actual engine operation, the accessory drive gearbox shaft extension is enclosed in a tube connected to the accessory gearbox which allows oil to return to the accessory gearbox. Since the accessory gearbox and the connecting tube are not used with the simulator, it was necessary to provide an oil seal around the accessory drive gearbox shaft extension to prevent oil loss, and to provide an external oil scavenge pump to return test oil from the gearbox to the sump.

Test-Oil System. The general configuration and location of the test-oil system with respect to the simulator is shown in Figure 2. The primary emphasis placed upon the design of the test-oil system was to provide a versatile system which would duplicate the temperatures and pressures in the J57 engine lubrication system.

Figure 4 presents a schematic of the automated AFAPL engine simulator test-oil system. All items of the system which are exposed to the lubricant are constructed of stainless steel with the exception of the test oil pressure pump and the gearbox scavenge pump. The O. D. of the stainless steel sump is copper-metallized for a distance extending

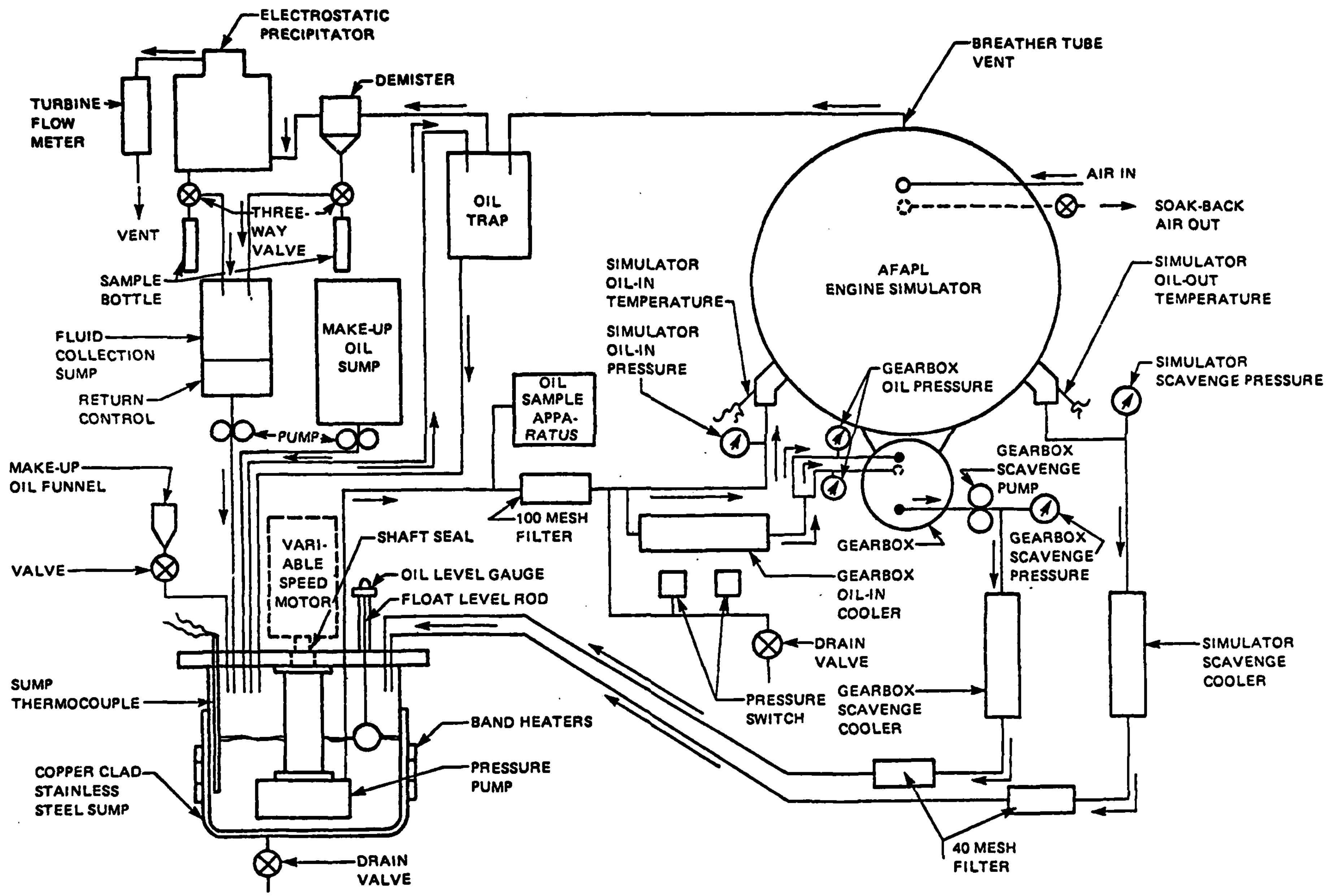

FIGURE 4. SCHEMATIC OF AUTOMATED AFAPL ENGINE SIMULATOR EXTERNAL TEST-OIL SYSTEM

approximately 6 in. (15.2 cm) from the sump bottom to provide improved heater efficiency and temperature uniformity. Heat is provided to the test-oil sump in the area of the copper clad by three 1500-watt band heaters conforming to the sump diameter.

A positive displacement gear pump (Brown and Sharpe 3S) is used in conjunction with a 3-hp variable-speed motor to provide test oil at a controlled 45 psi ($310X10^3$ Pa), to the simulator and gearbox. As shown in Figure 4, the pump is mounted inside the test-oil sump below the level of the test oil. A mechanical carbon seal is used to seal the pump shaft at the sump lid in order to permit measurement of seal air leakage in the simulator. The test-oil flow from the pressure pump passes through a 100-mesh screen filter and approximately 6 gal/min (22.7 l/min.) is directed to the oil inlet fitting of the simulator. The oil is scavenged from the No. 4-5 bearing compartment by the standard internal scavenge pump of the J57 engine and is returned to the test-oil sump after passing through an oil cooler and a 100-mesh screen filter.

Since the simulator is driven through the accessory drive gearbox, additional oil is supplied to the gearbox to provide increased cooling to the gears and bearings within the gearbox. Approximately 3 gal/min (11.4 l/min) of the oil flow from the pressure pump is utilized to provide the increased cooling for the gearbox. As shown in Figure 4, a portion of the oil flow from the 100-mesh screen filter (in the pressure line) is directed through an oil cooler and then to the gearbox. An external scavenge pump (Brown and Sharpe 2S), mounted on the bedplate below the level of the gearbox, returns the oil through an oil cooler and a 100-mesh screen filter to the test-oil sump.

The oil system within the simulator is the standard internal oil system (passages, fixed jets, and scavenge pump) used in the No. 4-5 bearing compartment area of the J57-43 except for the following changes:

- As stated previously the No. 4-1/2 bearing is not included in the AFAPL engine simulator; therefore, the normal oil flow from the No. 4-1/2 bearing is not included in the oil scavenged from the simulator.

- The J57-29 engine used at APL for the full- scale engine tests does not use two oil jets to lubricate the No. 5 carbon seal as does the J57-43 engine, therefore, the top oil jet to the No. 5 carbon seal in the simulator was capped in order to provide approximately the same amount of oil flow to the No. 5 carbon seal area as that obtained in the APL full-scale J57-29 engine. As discussed in a later section of this report, the oil flow from the top jet to the No. 5 carbon seal was redirected through a 0.076 in (0.193 cm) jet onto the main shaft towards the No. 4 sump. Redirecting this oil flow in the simulator provides cooling oil to the area of the I.D. of the conical section approximating the oil flow through the shaft, in this same area, from the No. 4-1/2 bearing in the full-scale engine.

The test-oil sump is sealed in order to permit the measurement of the No. 4-5 breather tube pressure in the test-oil system. The air leaking past the carbon seals into the test-oil section of the simulator is removed from the simulator by the over capacity scavenge pumps or is vented through the No. 4-5 compartment breather tube vent, as shown in Figure 4. The air-oil mist from the breather tube vent is directed to an oil trap which collects and gravity returns any oil droplets to the test-oil sump. The test-oil sump is also vented to the top of the oil trap. From the oil trap, air and oil vapors are directed to a demister, which removes approximately 1/2 of the air borne liquid from the vapors and then to an electrostatic precipitator which removes the remaining liquid from the vapors. The air from the electrostatic precipitator is then directed to a turbine type flow meter where measurements of air flow are taken periodically. Drains are provided on both the demister and the

precipitator to enable the fluid removed from the vapors to be collected in a common fluid collection sump. The fluid thus collected, is returned automatically to the test-oil sump by a computer controlled pump which is activated by a signal from a pressure transducer located in the return control system of the fluid collection sump. Samples of either the demister or precipitator fluids can be taken manually, if desired, by use of the three-way valves provided.

Test-oil samples (40 ml each) are automatically taken from the oil pressure line, leading from the sump to the 100-mesh filter, approximately three minutes prior to each 5-hr shutdown for soakback. The samples taken are used to monitor viscosity, neutralization number, and iron content. Make-up oil is added automatically to the test-oil sump from the make-up oil sump (see Figure 4), approximately five minutes after the 5-hr shutdown for soakback, to compensate for loses resulting from normal consumption and the samples drawn.

Air System. Filtered laboratory air is directed through the No. 4 end closure (see Figure 1) to a manifold ring which distributes the incoming air over the finned air heaters in the No. 4 bearing area. The air exits the simulator through the test-oil system and the No. 4-5 bearing compartment breather tube vent previously described.

An emergency air blow down system is included in the engine simulator facility. This system is designed for use in the event that the laboratory air system becomes inoperative. Four high pressure air bottles are manifolded together. In the event laboratory air is lost, the bottled air is automatically turned on by the computer. The quantity of emergency air available is sufficient to operate the simulator for approximately 2 hr, perform a 1-hr soakback, or, cool the simulator down during an emergency stop, if required.

Breather Tube. The J57 engine uses a rather complex configuration for the No. 4-5 bearing area breather tube (see Figure 1) by utilizing one of the diffuser case struts. Plates are welded at both the upper and lower portions of the strut. A tube is welded near the center of lower plate of the strut and extended downward into the No. 4 bearing compartment. This is the basic breather tube design. One serious problem related to this basic design is that it is almost impossible to completely clean the teardrop-shaped strut, primarily due to the inability to get a cleaning tool into the teardrop portion of the strut.

In an effort to alleviate cleaning of the basic breather tube design Pratt and Whitney designed a "slip-in breather tube." This modification is used in the AFAPL engine simulator and greatly simplifies the cleaning of the tube since it can be easily removed from the diffuser case strut.

Heating System. In order to simulate actual engine operating conditions, it is necessary to add heat and control the temperature in the following areas of the simulator:

- No. 4 bearing-seal area
- Conical section
- No. 5 bearing-seal area
- Breather strut

Information related to these temperature controlled areas are discussed in the following paragraphs.

No. 4 Bearing-Seal Area. The No. 4 compartment is heated by five finned air heating elements (Figure 1) utilizing monel sheath and fins capable of a maximum surface temperature of 1050°F (566°C). These heaters have a combined maximum capacity of 25.6 kW. By carefully directing the air entering the No. 4 bearing-seal area through the manifold ring across

the finned heating elements the desired maximum air temperature of 800°F (427°C) is attained. The heater rings are attached to the No. 4 end closure.

Two 750W band heaters are clamped around the No. 4 bearing housing assembly to assist in producing bearing outer race temperatures similar to those obtained in the APL full-scale engine test.

Conical Section. The outside surface of the conical section is heated by five band heaters having a combined maximum capacity of 6.5 kW. In order to provide a more uniform flow of heat to the conical section, a 3/8 in. (1.0 cm) thick layer of copper was metallized to the entire outside surface of the tapered portion of the conical section. Cylindrical steps were then machined in the copper layer to accomodate the five band heaters.

No. 5 Bearing-Seal Area. Approximately one-half of the heated air in the No. 4 bearing-seal area flows through the heated annulus of the conical section to the No. 5 bearing-seal area; therefore, only a small amount of heat, to make up for heat losses, is required for the No. 5 bearing-seal area.

The No. 5 compartment is heated by two finned air heating elements, similar to those used in the No. 4 compartment, having a combined maximum capacity of 8.2 kW. The heater rings are attached to the No.5 end enclosure and fit inside the turbine nozzle inner case (Figure 1) upon assembly of the simulator.

Breather Tube Strut. The breather tube strut is heated by means of a clam-shell type open wire electric resistance heater. The heater enclosure is trapezoidal shaped to fit around the strut. Approximately 1 kW is required to maintain a controlled strut skin temperature of 650°F (343°C).

Operating Procedures

General. The AFAPL engine simulator test is patterned after the 100-hr, 9120-6000 rpm cycling test procedure used at APL for the full-scale engine tests. Temperatures are controlled in slected areas of the engine simulator in order to approximate the temperature profiles obtained in APL full-scale engine tests. The standard test duration is considered to be 100 hr in order to allow comparison of the engine simulator test results with the results obtained from full-scale APL engine test results. However, extended-duration tests of up to 350 hr have also been conducted using the engine simulator. Selected oil wetted parts within the engine simulator are visually rated for deposits and color photographs are taken at the end of test. Samples of test oil are drawn periodically and the viscosity and neutralization number determined. A description of the AFAPL engine simulator test is presented in the following paragraphs.

Test Preparation. A number of preliminary steps are performed prior to starting an engine simulator test. All of the oil wetted parts in the engine simulator and test-oil system are thoroughly cleaned and air dried prior to assembly of the components. The heat exchangers used in the test oil system are pressure checked after cleaning to insure that no leaks exist between the oil to water heat transfer tubes. The oil filter screens used for the simulator oil in, simulator oil out, and the gearbox oil out are cleaned, weighed, and their weights recorded. New thermocouples are made and installed in the engine simulator. Thermocouples located in the air and test-oil systems are checked and replaced as necessary. The No. 4 and No. 5 carbon face seals are checked for flatness of the sealing face and lapped if necessary. The height of the carbon seal face of both the No. 4 and No. 5 carbon seals is measured at three indexed locations, 120° apart, and recorded. The seal plates used with the No. 4 and No. 5 carbon seals are visually inspected for nicks, dents, and smearing of the chrome plated sealing surface. The seal plates are then checked for flatness of the sealing surface and lapped if necessary. The complete seal assemblies

are then individually checked for leaks using a special test fixture. Following these specific inspections and a visual inspection of all parts within the simulator, the simulator is assembled in accordance with T.O. 2J-J57-56. The test-oil system is assembled and the lubricant to be evaluated is added to the test-oil sump.

Test Temperatures. A total of 54 temperatures are continuously monitored and recorded during an engine simulator test. Figure 5 presents the general locations for the 34 thermocouples inside the engine simulator. Thirteen thermocouples are placed in various locations throughout the test-oil system. Three thermocouples are placed under bolt heads located on the front, rear, and top (near bearing outer races) of the gearbox. The remaining four thermocouples are located on the two drive motors and the input shaft pillow block bearings.

Controlled Test Temperatures. Temperatures are controlled in selected areas of the engine simulator in order to approximate the temperature profile obtained in APL full-scale engine tests. The location and the temperature or the controlled temperature areas of the engine simulator during test, are as follows:

Location	Thermocouple Number	Controlled Temperature, °F (C)
No. 4 Air	3	800 (427)
No. 4 Bearing Heater	5	800 (427)
Concial Outer Surface	12	800 (427)
No. 5 Air	23	850 (454)
Breather Tube Strut	32	650 (343)
Test Oil Sump	41	300 (149)

Test Sequence. As mentioned earlier, the test sequence used with the AFAPL engine simulator is patterned after the 100-hr, 9120-6000 rpm cycling

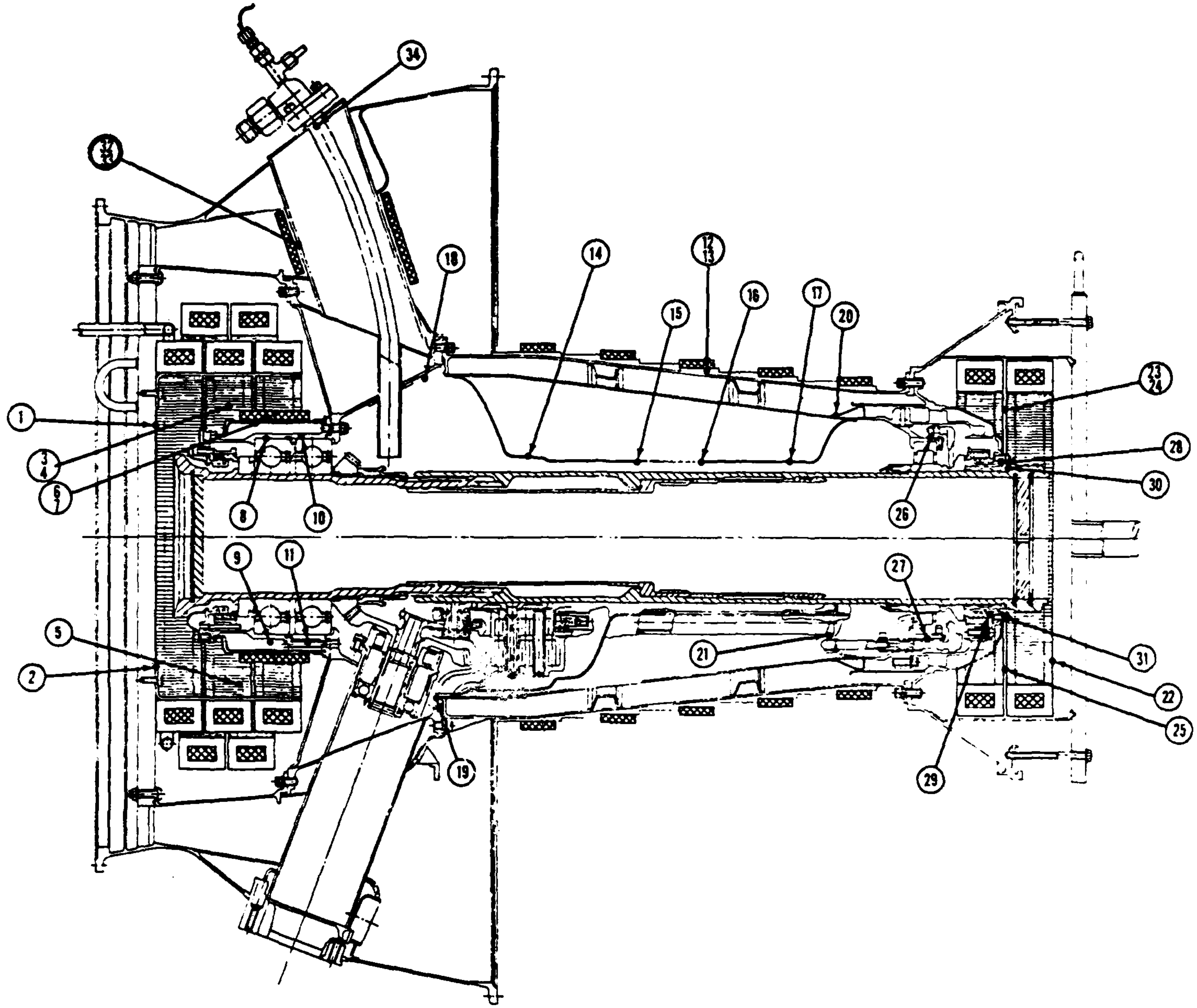

FIGURE 5. AFAPL ENGINE SIMULATOR THERMOCOUPLE LOCATIONS

test procedure used at APL for the full-scale engine tests. Briefly, the test oil system heaters, the air heaters, the No. 4 bearing heaters, the conical outer surface heaters, and the breather tube strut heater are all turned on and preheated for a short period of time (approximately 20 min). The test-oil pressure pump and gearbox scavenge pump are started. Within approximately 15 seconds from the time the test-oil pressure pump is started, the drive system of the simulator is started and the simulator speed brought up to 9120 rpm and the air pressure is increased to 20 psi. These conditions are maintained for 25 minutes. The speed is then reduced to 6000 rpm for a period of 5 minutes. This speed cycle is repeated three times for a total heated operating period of two hours. At that time the power to all heaters is turned off and one speed cycle is run without heat. At the end of the 30-minutes operating period without heat, the simulator is stopped and a 1-hr temperature soakback is made. The valve in the air-out line on the No. 5 end cover is opened and the air pressure is reduced to 6 psi for the first 30 minutes of the soakback period and then further reduced to 3 psi for the remaining 30 minutes of the soakback period. The 1-hr soakback period is not counted as operating test time. The 2.5-hr operating test cycle and 1-hr soakback are repeated 40 times to complete a 100-hr simulator test.

At the end of test, whether 100-hr or an extended duration test, the simulator is disassembled and color photographs of the rated items are taken prior to the visual deposit inspection.

Test Termination. Simulator tests are normally conducted for 100-hr, or for longer predetermined periods, as required. However, a test may be terminated early if the 5-hr test-oil sample indicates a 100° (37.8°C) viscosity increase of 50 percent or the neutralization number exceeds 10 mg KOH/g.

Test Procedure Variations. Numerous minor variations were made to the test procedure used with the original, manually operated AFAPL engine

simulator. These variations were made in an effort to, (1) improve the temperature profile within the engine simulator such that it provided a better approximation of the temperature profile within the APL full-scale engine tests, (2) adapt available J57-43 engine parts as necessary to simulate the oil flows in the J57-29 engine (used in the full-scale engine tests), and (3) obtain correlation of the engine simulator used oil analyses with those obtained during the full-scale engine tests.

The following variations (A through E) to the basic test procedure were used with the manually operated AFAPL engine simulator:

Procedure A

1. The initial test-oil sump charge was 5 gal.

2. The standard internal oil system in the No. 4-5 bearing compartment area of the J57-43 was used. Since the No. 4-1/2 bearing is not included in the simulator, the normal oil flow from the No. 1/2 bearing was not included.

3. A forced oil make-up schedule, scaled to the oil make-up normally required by the full-scale engine test, was used.

4. The fluids collected in the demister, precipitator, and oil trap were sampled for viscosity and neutralization number determinations but were not returned to the test-oil sump.

Procedure B

1. The test-oil system was modified such that the oil from the oil trap in the engine simulator vent line was continuously returned to the sump. The fluids collected in the demister and precipitator were sampled for viscosity and neutralization number determinations and the fluids remaining after sampling were returned to the sump.

2. All other test conditions were the same as Procedure A.

Procedure C

Same as Procedure B except initial test-oil sump charge was incresased to 6 gal.

Procedure D

1. The initial test-oil sump charge was 6 gal.

2. The standard J57-43 internal oil system was modified by capping the top oil jet to the No. 5 carbon seal, thereby approximating the oil flow to the No. 5 carbon seal area in the APL full-scale J57-29 engine.

3. The forced oil make-up schedule was not used. Test oil was added at each 5-hr test interval, after samples were drawn and the fluids from the demister and precipitator were returned to the sump, to compensate for losses resulting from consumption and the samples drawn.

Procedure E

Same as Procedure D except for the following:

1. The oil from the top oil jet to the No. 5 carbon seal was redirected through a 0.076 in. jet onto the main shaft towards the No. 4 sump in the area of the No. 17 thermocouple. Redirecting this oil flow provides oil to the area of the I.D. of the conical section approximating the flow through the shaft from the No. 4-1/2 bearing in the full-scale engine.

2. A plug was placed in the I.D. of the main shaft in the No. 5 seal area in an effort to reduce the temperature of the main shaft. A 1/8 in. hole was drilled in the plug to relieve any possible pressure increase within the shaft.

Procedure Auto I

This procedure represents the automated version of Procedure E, in that, the computer control software was written to duplicate, as nearly as possible, the earlier manual operation of the simulator temperature, pressure, and speed controls. No known differences were designed into the operating portion of the test. The only differences are in the mechanical methods the 5-hr samples are taken and the test-oil make-up is added to the sump.

Deposit Demerit Rating Procedure

Upon completion of an engine simulator test the engine simulator is disassembled and selected oil wetted parts are visually rated for deposits. The deposit demerit rating system used by APL for full-scale engine testing is also used to numerically describe the lubricant deposits which accumulate on the rated parts of the engine simulator. The demerit rating numbers used to describe the different types and thicknesses of deposits obtained in the full-scale engine tests conducted at APL and the AFAPL engine simulator test are summarized in Table 1.

The following 17 oil wetted engine simulator parts are rated for deposits:

- No. 4 Forward Bearing
- No. 4 Aft Bearing
- No. 5 Bearing
- No. 4 Seal
- No. 5 Seal
- No. 4 Sump
- No. 5 Bearing Support Forward and Aft
- No. 4-5 Scavenge Pump
- No. 4 Compartment

TABLE 1. DEMERIT RATING NUMBERS USED FOR NUMERICALLY DESCRIBING DEPOSITS

Deposit Description	Demerit Rating Number
Clean	0.0
Very light varnish - straw colored	1.0
Light varnish - amber colored	1.2
Medium varnish - tan colored	1.4
Heavy varnish - brown, 0.001 in. (0.0025 cm) depth	1.7
Very heavy varnish - black <0.002 in. (0.005 cm) depth	2.0
Light soft sludge - wipes easily, little depth	1.5
Medium soft sludge - wipes with pressure, <0.016 in. (0.040 cm) depth	1.8
Heavy soft sludge - difficult to wipe, >0.016 in. (0.040 cm) depth	2.2
Light hard sludge - <0.016 in. (0.040 cm) depth	2.5
Medium hard sludge - 0.016 in. (0.040 cm) to 0.062 in. (0.159 cm) depth	3.0
Heavy hard sludge - >0.062 in. (0.159 cm) depth	3.5
Light gritty deposit - <0.016 in. (0.040 cm) depth	4.0
Medium gritty deposit - 0.016 in. (0.040 cm) to 0.062 in. (0.159 cm) depth	5.0
Heavy gritty deposit - >0.062 in. (0.159 cm) depth	6.0
Light smooth or wavy deposit - <0.016 in. (0.040 cm) depth	5.5
Medium smooth or wavy deposit - 0.016 in. (0.040 cm) to 0.062 in. (0.159 cm) depth	7.0
Heavy smooth or wavy deposit - >0.062 in. (0.159 cm) depth	8.5
Light blistered deposit - <0.016 in. (0.040 cm) depth	6.5
Medium blistered deposit - 0.016 in. (0.040 cm) to 0.062 in. (0.159 cm) depth	8.0
Heavy blistered deposit - >0.062 in. (0.159 cm) depth	9.5
Light flaked deposit - <0.016 in. (0.040 cm) depth	9.0
Medium flaked deposit - 0.016 in. (0.040 cm) to 0.062 in. (0.159 cm) depth	12.0
Heavy flaked deposit - >0.062 in. (0.159 cm) depth	15.0

- No. 5 Compartment
- No. 4-5 Scavenge Pump Screen
- No. 4-5 Breather Tube
- No. 4-5 Breather Tube Elbow
- Tower Shaft
- Tower Shaft Strut
- Conical Section I.D.
- Rear Shaft

The deposit rating for each part or area rated is obtained by selecting a demerit rating number or numbers, ranging from 0 to 15 (Table 1), to describe the types and thicknesses of deposits present on the part. The demerit number is then multiplied by the estimated percent area covered by that deposit. In the event that more than one type or thickness of deposit is present on the area being rated, the rating for that part or area is the total of the individual ratings. The inspection accounts for 100 percent of each oil wetted part or area being inspected. When the part being rated is broken down into various sub items and rated areas, such as the No. 4 bearings (inner race, outer race, retainer, and balls), the average rating is obtained for each sub item and the overall average rating is obtained for each sub item and the overall average rating for the part determined by averaging the ratings obtained for each sub item. The overall engine simulator rating is obtained by adding the following individual ratings:

- Total bearing rating
- Total seal rating
- Total sumps and pump rating
- Total compartment rating
- Total screen rating

The ratings obtained for the breather (No. 4-5 elbow and No. 4-5 tube), miscellaneous (tower shaft and tower shaft strut), conical I.D. and

rear shaft are not included in the overall engine simulator rating. These parts are not rated in the APL full-scale engine tests; therefore, they are not included in the overall engine simulator rating but are reported for added information.

Test Data Reported

A test report is generated by and printed out by the computer after manual inputs are completed by the operator at the end of each test. The typical test report includes the following information:

- Test summary data sheet
- Test lubricant consumption data
- Filter weight data
- Viscosity data at 5-hr intervals
- Neutralization number and iron content at 5-hr intervals
- Plot of viscosity versus test time
- Plot of neutralization number versus test time
- Detailed deposit rating
- Average data (temperature, pressure, rpm) from 63 individual sensors
- Carbon seal wear measurements
- Test-oil system filter weights
- Average soakback temperature plots
- A listing of the low and high, inner and outer limits for the 63 individual temperature, pressure, and rpm sensors

In additon to the aforementioned data, color photographs of the rated simulator parts are included in each report submitted to APL.

TEST LUBRICANTS

Twenty-four lubricants have been evaluated to date in the AFAPL engine simulator. APL full-scale engine test data were available for eight of the lubricants evaluated. The full-scale engine tests were conducted, in some cases, on different batches of the same lubricant formulation as noted in later sections of this report. Table 2 presents a description of the lubricants included in the program along with their respective initial viscosities and neutralization number data.

TABLE 2. DESCRIPTION OF TEST LUBRICANTS

Oil Code	Viscosity, cs 100°F (37.8°C)	Viscosity, cs 210°F (98.9°C)	Neut. No., mg KOH/g	Description
0-62-6	17.8	4.7	0.29	MIL-L-7808E
0-67-7	17.3	4.6	0.28	Different batch of 0-62-6
0-67-20	13.5	3.2	0.21	MIL-L-7808G
0-67-21	12.9	3.2	0.24	MIL-L-7808G
0-67-23	13.5	3.3	0.46	Different batch of 0-67-20
0-68-7	13.8	3.8	0.15	MIL-L-7808G
0-68-13	14.6	3.6	0.23	MIL-L-7808G
0-70-2	13.9	3.7	0.26	MIL-L-7808G
0-71-2	13.4	3.3	0.03	MIL-L-7808 Type
0-72-2	33.2	6.0	0.16	MIL-L-27502 Type
0-72-8	14.0	3.7	0.24	Different batch of 0-70-2
0-72-9	15.3	3.6	0.12	MIL-L-7808 Type
0-72-13	14.7	3.5	0.12	MIL-L-7808 Type
0-73-1	33.8	6.1	0.04	Different batch of 0-72-2
0-74-2	13.6	3.4	0.05	Different batch of 0-68-7
0-76-1	13.5	3.6	0.26	Different batch of 0-70-2
0-79-16	13.4	3.2	0.21	Different batch of 0-67-20
0-79-17	13.5[a]	--	0.04	MIL-L-7808H
0-79-20	14.1[a]	--	0.15	MIL-L-7808H
0-80-2	12.2[a]	--	0.20	MIL-L-7808H
0-81-1	11.8[a]	--	0.13	MIL-L-7808 Type
0-81-15	12.8[a]	--	0.14	MIL-L-7808 Type
0-82-2	12.8[a]	--	0.05	Different batch of 0-68-7
0-82-3	14.3[a]	--	0.04	MIL-L-7808 Type
ATL-6040	13.1	3.4	0.24	Different batch of 0-70-2
ATL-8152	13.9	3.3	0.04	MIL-L-7808 Type

(a) Viscosity determined at 104°F (40°C).

TEST RESULTS AND DISCUSSION

General

Twenty-four lubricants have been evaluated to date using the AFAPL engine simulator. A total of 31 tests have been conducted, accumulating over 4300 test hours on the engine simulator rig, during the evaluations conducted on the 24 lubricants.

Numerous short duration tests (8 hr or less) to check the general operation of the simulator hardware and manual control systems, including the soakback procedure, conducted in the early operating period of the simulator and reported in Reference 1 will not be repeated in this report. However, all of the simulator lubricant evaluations, conducted manually or using the automated systems, are included in this report to provide a complete set of AFAPL engine simulator data in one report.

Lubricant Evaluation Tests

As mentioned earlier, 31 AFAPL engine simulator tests have been conducted to date. Eighteen of these tests were conducted using the manual control system originally developed for the simulator, while the remaining tests were conducted using the H-P 1000 computer to manage and control the simulator systems which were earlier manually controlled by trained technicians.

Twenty-four lubricants have been evaluated in the AFAPL engine simulator to date, using the test procedures described earlier in this report. Eight of the 24 lubricants evaluated were selected on the basis of APL full-scale engine test data being available on them, thereby making it possible to compare the results obtained with the engine simulator with those obtained from full-scale engine tests.

A summary of the results obtained from the 31 AFAPL engine simulator tests is presented in Table 3. The different test procedure variations used during the course of evaluating the different lubricants are noted in Table 3. Procedure variations D, E, and Auto 1 do not vary greatly from each other; and, as such can be considered to be essentially the same for the purpose of test result comparisons.

Two lubricants were originally selected to be run using the automated AFAPL engine simulator to provide results which could be compared with those obtained earlier using procedures D and E. Based upon the deposit ratings obtained earlier, lubricants 0-73-1, a "clean" oil, and 0-67-7, a "dirty" oil, were selected to represent the two extreme conditions of interest. The results obtained for 0-73-1 using Auto 1 procedure (Test No. 23) are for all practical purpose the same as those shown for Test 11 conducted earlier using procedure E. The deposit rating of 27.4 obtained for 0-67-7 using the Auto 1 procedure (Test No. 24) confirmed the "dirty" oil rating of 24.4 obtained earlier (Test No. 14) using procedure E. The end of test results shown for 0-67-7 using the Auto 1 procedure (Test No. 24) appears to provide a significant difference in the results shown for the lubricant viscosity and neutralization number when compared with Test No. 14. However, the 5-hr lubricant sample values (included in the individual test report for Test No. 24) showed that the 80-hr lubricant sample, just 10 hr before the test was terminated, provided -20.2 percent viscosity change and +4.16 neutralization number change, much the same as those shown in Table 3 for 0-67-7 using procedure E. Additional data that shows correlation of the manually operated procedures and the automated procedure is presented for lubricants 0-67-23 and 0-79-16, different batches of the same lubricant formulation, after 100-hour and 250-hour operation (see Test Nos. 6, 25, and 36). Also, very good agreement of data is evident when comparing Test No. 13 (100-hr) using 0-74-2 with Test No. 34 using 0-82-2, again different batches of the same lubricant formulation. Additional data will be required from the engine simulator before the test repeatability can actually be determined.

TABLE 3. SUMMARY OF AFAPL ENGINE SIMULATOR TESTS

Lubricant	Test Procedure Variation	Test Time, hr	Deposit Rating	100°F Viscosity Change, %	Neut. No. Change, mg KOH/g	Sump Iron Content, ppm max(a)	Test No.
0-67-7	E	100	24.4	-18.8	+0.60	48 (95)	14
0-67-21	D	100	19.7	+10.7	+0.29	10 (100)	9
	D	250	21.8	+12.7	+0.63	10 (105)	9
0-67-23	A	100	17.3	+6.9	-0.16	10 (80)	3
	D	100	18.2	+5.6	-0.19	4 (85)	6
	D	250	21.1	+8.9	+0.07	5 (120)	6
0-68-13	E	100	18.5	-3.6	+0.37	54 (100)	12
	E	225[b]	20.3	-0.2	+1.42	130 (225)	12
0-70-2	D	90[c]	18.8	+78.1	+35.14	48 (90)	8
	E	75[d]	17.2	+46.2	+23.98	50 (75)	10
0-71-2	B	100	19.9	+9.7	+1.17	68 (45)	4
	C	100	18.6	+7.4	+0.81	4 (30)	5
	D	90[c]	23.0	+1434.6	+51.16	90 (90)	7
0-72-8	E	150[e]	25.3	-0.5	+2.29	2750 (65)	17
0-72-9	E	100	19.0	-6.2	+0.19	58 (95)	15
	E	147.5[f]	21.2	+9.1	+0.31	120 (147.5)	15
0-72-13	E	100	20.0	+6.7	+0.33	80 (100)	16
	E	250	19.7	+11.1	+0.63	80 (100)	16
0-73-1	E	100	16.0	+5.1	+0.45	40 (100)	11
	E	250	19.8	+17.1	+1.30	195 (250)	11
0-74-2	E	100	18.0	+7.4	+0.45	48 (100)	13
	E	250	19.7	+14.1	+2.40	115 (250)	13
0-76-1	E	61[g]	23.0	-12.6	+0.83	1200 (61)	18
ATL-6040	E	100	19.2	+1.0	+1.31	82 (100)	19
ATL-8152	E	100	18.9	+8.0	+0.17	57 (95)	22
0-67-7	Auto 1	90[h]	27.4	+44.3	+39.29	48 (75)	24
0-73-1	Auto 1	100	15.7	+5.2	+0.89	23 (100)	23
0-79-16	Auto 1	100	17.6	8.0	+0.24		36
	Auto 1	250	25.4	+10.4[i]	+0.81	36 (105)	25
	Auto 1	350	34.3	+14.6	+1.23	270 (350)	26
0-79-17	Auto 1	100	14.4	+9.0	+0.17	7 (85)	29
0-79-20	Auto 1	100	19.7	+3.0	+0.25	14 (65)	28
0-80-2	Auto 1	100	15.6	+6.0	+0.17	12 (55)	27
0-81-1	Auto 1	100	23.2	+11.5	+0.66	4 (25)	31
0-81-15	Auto 1	41.5	15.2	+2.5	+0.16	11 (40)	30
	Auto 1	100	17.2	+7.4	+0.30	1 (55)	32
0-82-2	Auto 1	100	17.5	+10.0	+2.01	9 (75)	34
0-82-3	Auto 1	100	15.2	+12.8	+0.42	25 (80)	35

Test Procedure

A. Sump 5 gal., standard J57-43 oil system, forced oil make-up, collected vent fluids not returned.
B. Sump 5 gal., standard J57-43 oil system, forced oil make-up, collected vent fluids returned.
C. Sump 6 gal., standard J57-43 oil system, forced oil make-up, collected vent fluids returned.
D. Sump 6 gal., capped No. 5 top seal jet, no forced oil make-up, collected vent fluids returned.
E. Sump 6 gal., No. 5 top seal jet oil directed to I.D. of conical, no forced oil make-up, collected vent fluids returned.
Auto 1. Same as E except computer management of all simulator control systems.

(a) Number in parentheses indicate the earliest test time at which maximum concentration occurred.
(b) Test terminated at 225 hr due to repeated cracks occurring in conical section front flange.
(c) Test terminated at 90 hr due to excessive increases in viscosity and neutralization number of sump sample.
(d) Test terminated at 75 hr due to excessive increases in viscosity and neutralization number of sump sample.
(e) Test terminated at 150 hr. No 100-hr intermediate inspection made.
(f) Test terminated at 147.5 hr due to fatigue spall in outer race of the No. 4 forward bearing.
(g) Test terminated at 61 hr due to excessive cage wear of No. 4 aft bearing.
(h) Test terminated at 90 hr due to excessive increase in viscosity and neutralization number of sump sample.
(i) Viscosity determined at 104°F (40°C) for Test No. 25 and all subsequent tests.

Correlation of Simulator and Engine Test Results

Due to the limited amount of data available from both the AFAPL engine simulator and full-scale engine test, only general statements can be made with respect to correlation of test results.

Repeat test data from APL full-scale engine tests are available on only one lubricant, 0-67-20 (an earlier batch of 0-67-23), since the numerical rating system has been in use at APL. Four APL full-scale engine tests on lubricant 0-67-20 gave the following deposit ratings:

Test No.		Total Engine Deposit Rating
1		83.1
2		79.4
3		89.4
4		86.4
	Avg =	84.6

These four engine deposit ratings provide a standard deviation of 4.3 and a 95 percent confidence interval about the mean of ± 4.2. These data indicate an excellent repeatability capability of the full-scale engine test. However, additional data would be required using other lubricants before an overall test repeatability statement could be reliably estimated.

Seven lubricants, 0-67-21, 0-67-23, 0-68-13, 0-70-2, 0-71-2, 0-73-1, and 0-74-2, which have been evaluated in the AFAPL engine simulator have also been evaluated in the APL full-scale engine. One lubricant, 0-67-7, also has engine data available, but was run in the full-scale engine prior to the use of the numerical rating system. Therefore, only general data are available for 0-67-7 with respect to full-scale engine deposit ratings.

Table 4 presents a comparison of the 100-hr AFAPL engine simulator deposit ratings with the 100-hr full-scale engine deposit ratings. The engine simulator deposit ratings shown in Table 4 are from tests using only

TABLE 4. COMPARISON OF AFAPL ENGINE SIMULATOR DEPOSIT RATINGS WITH FULL-SCALE ENGINE DEPOSIT RATINGS

Lubricant	Deposit Rating		
		Full-Scale Engine	
	Simulator	4-5 Area[(a)]	Total[(b)]
0-67-7 (0-62-6)	24.4	(c)	(c)
0-67-21	19.7	17.6	68.5
0-67-23 (0-67-20)	17.9[(d)]	18.9[(e)]	84.6[(e)]
0-68-13	18.5	16.6	81.6
0-70-2	18.4[(f)]	16.0	65.5
0-71-2	23.0	24.6	97.3
0-73-1 (0-72-2)	16.0	15.5	75.2
0-74-2 (0-68-7)	17.8[(g)]	17.8	66.2

Lubricant code is parentheses indicate code of engine test lubricant if different from simulator test lubricant code.

(a) Deposit rating for the 4-5 area of the full-scale engine test.
(b) Total deposit rating for all rated areas of the full-scale engine test.
(c) Engine test performed prior to the initiation of the numerical rating system at APL.
(d) Average of two simulator tests (Nos. 6 and 36).
(e) Average of four engine tests
(f) Average of three simulator tests (Nos. 8, 10, and 19).
(g) Average of two simulator tests (Nos. 13 and 34).

the test procedures D, E, and Auto 1 which represent data from tests using the best approximation of actual J57-29 oil flows and temperature profiles. The deposit ratings shown for the full-scale engine are presented in two columns. One column shows the deposit rating for just the 4-5 bearing area from the engine test, and the other column shows the total deposit rating for all the rated areas of the full-scale engine. The deposit rating shown for the engine simulator can be compared directly with the ratings shown for the 4-5 area of the engine test since the rated areas included in both ratings are exactly the same. Figure 6 presents a plot of the AFAPL engine simulator deposit ratings versus the deposit ratings of the 4-5 area from full-scale engine tests. The degree of correlation, shown in Figure 6, is based on the calculated correlation coefficient[3], expressed as a percent value. This statistic is a measure of the collinearity of data, with 100 percent representing exact correlation (not necesaryily at a 1:1 ratio) and 0 percent indicating no correspondence. The equation used to obtain the correlation coefficient statistic (γ) is given as

$$\gamma = \frac{(n\Sigma xy - x\Sigma y)\ 100}{\sqrt{[n\Sigma x^2 - (\Sigma x)^2]\ [n\Sigma y - (\Sigma y)^2]}}$$

where n is the number of data pairs.

The dashed line in Figure 6 is the linear regression line for the data pairs plotted. The calculated correlation coefficient is shown to be 87.4 percent, which indicates very good correlation of the engine simulator deposit ratings with the 4-5 area deposit ratings from full-scale engine tests.

It was shown earlier[1] that the 4-5 area of the full-scale engine contributed 20.3 to 26.9 percent of the total engine deposit rating with

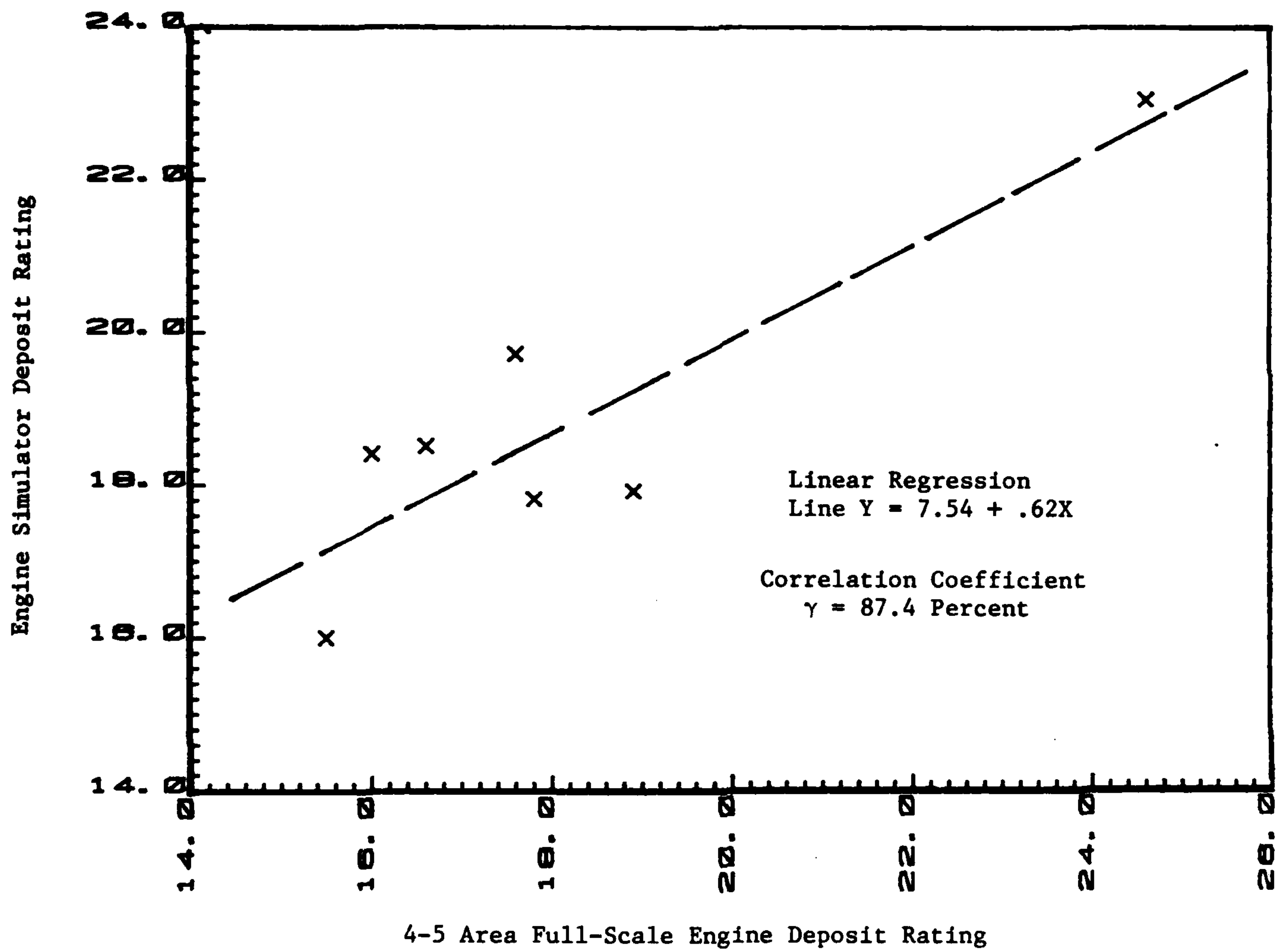

FIGURE 6. AFAPL ENGINE SIMULATOR DEPOSIT RATINGS VERSUS DEPOSIT RATINGS OF THE 4-5 AREA FROM FULL-SCALE ENGINE TESTS

the overall average being 23.2 percent. If the only deposit ratings available were from the 4-5 area of the engine, a reasonable estimate of the total engine deposit rating could be made by multiplying the deposit rating for the 4-5 area by the reciprocal of .232, or 4.31. Further, since the AFAPL engine simulator ratings have been shown to provide a good correlation with the deposit ratings obtained from the 4-5 area of the engine, multiplying the engine simulator ratings by the same factor, 4.31, should also provide a reasonable estimate for the total engine deposit rating. The estimated total engine deposit ratings from the data available are shown in Table 5 along with the actual total engine deposit ratings. These data are compared graphically in Figure 7. According to APL engine test data, 0-71-2 is the only lubricant which has failed the full-scale engine test since the numerical rating procedure has been in use. All other lubricants included in Figure 7 have passed the APL engine test. The actual deposit rating number which is considered to indicate a failure in the APL engine test is still under study at APL: however, it must lie between 84.6, the highest deposit rating for any lubricant which passed the APL engine test, and 97.3, the deposit rating for 0-71-2 which failed the engine test. If it is assumed for this report that the upper total engine deposit rating limit for a "pass" is as low as 85, then the "pass-fail" line would be shown by the dashed line in Figure 7. Although the estimated total engine deposit ratings obtained from the AFAPL engine simulator data, or the 4-5 area data from the full-scale engine tests do not provide the same relative ranking for the lubricants which passed the APL engine test, the estimated total engine deposit ratings for these lubricants indicate they would all pass the full-scale engine test. The estimated total engine deposit ratings also indicate that lubricant 0-71-2 would fail the engine test, which is confirmed by the engine test results. In addition, the estimated total engine deposit rating of 105.2 for lubricant 0-67-7 (see Table 5), from the AFAPL engine simulator data, indicates that 0-67-7 would fail the APL engine test. This lubricant originally passed the engine test in 1962, prior to the use of the numerical deposit rating procedure, and was included in the Qualified Products List (QPL) for MIL-L-7808D

TABLE 5. COMPARISON OF ESTIMATED AND ACTUAL TOTAL ENGINE DEPOSIT RATINGS

Lubricant	Estimated Total Engine Deposit Rating[a] Simulator	Estimated Total Engine Deposit Rating[a] 4-5 Engine Area	Actual Total Engine Deposit Rating
0-67-7	105.2	--	--
0-67-21	84.9	75.8	68.5
0-67-23	77.1	81.5	84.6
0-68-13	79.7	71.6	81.6
0-70-2	79.3	69.0	65.5
0-71-2	99.1	106.0	97.3
0-73-1	69.0	66.8	75.2
0-74-2	76.7	76.7	66.2

[a] Estimated total engine deposit rating obtained by multiplying the simulator deposit rating and the 4-5 engine area deposit rating by 4.31.

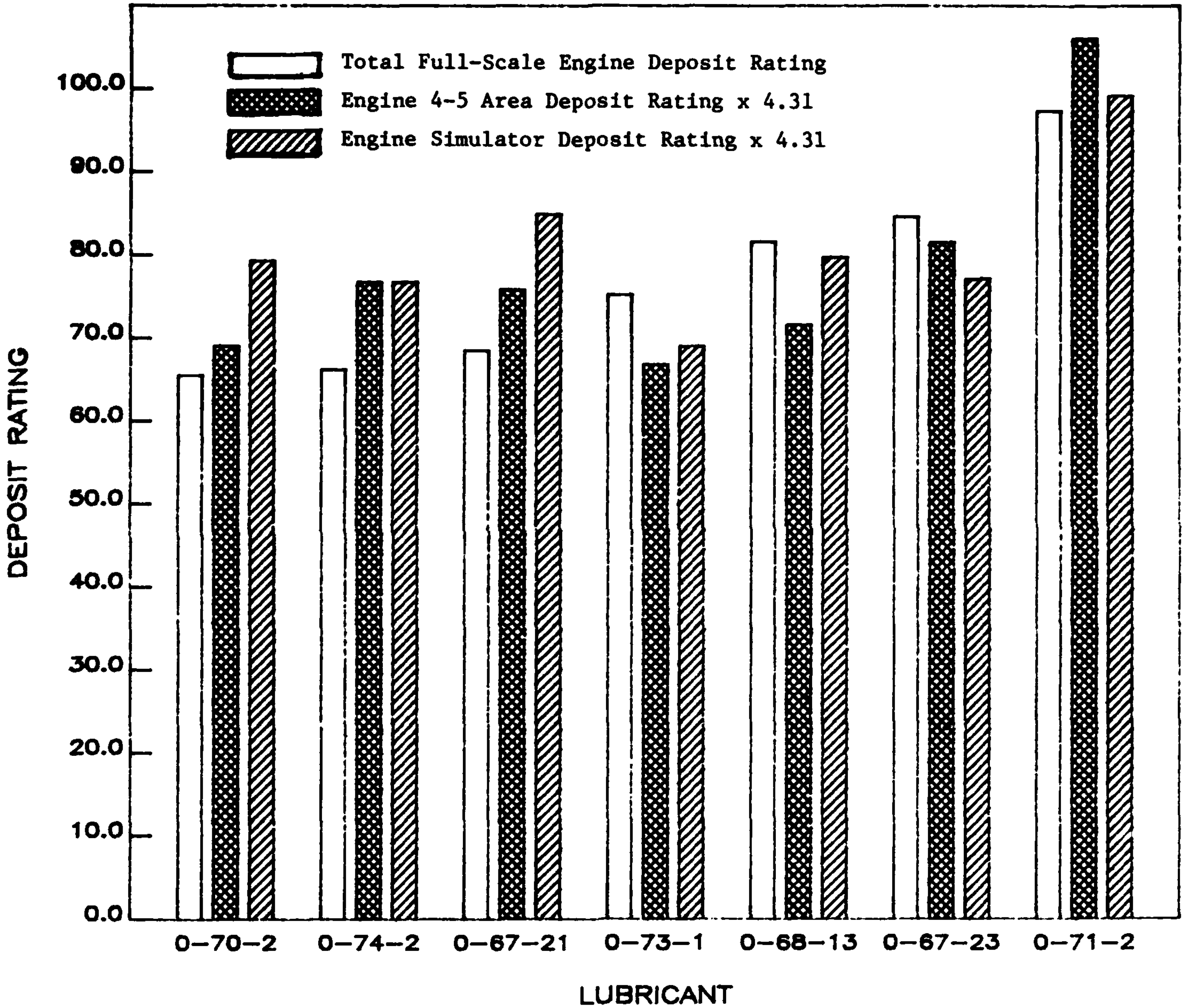

FIGURE 7. COMPARISON OF ESTIMATED AND ACTUAL TOTAL ENGINE DEPOSIT RATINGS

lubricants. It is understood that the 0-67-7 formulation was included as a QPL lubricant until late 1967 when it was removed from the list due to its failure to meet the bearing deposition test requirements of the MIL-L-7808G specification. The bearing deposition test deposit ratings obtained by SwRI[4] for lubricants 0-62-6 and 0-67-7 were 90 and 97, respectively, while the MIL-L-7808G specification stated that the "overall deposit demerit rating shall not exceed 80."

Extended Duration Tests. Ten extended duration tests (over 100-hr duration) have been run to determine the effect of extended test time on the deposition characteristics of selected lubricants, as shown in Table 3. All of the extended duration tests except Test No. 26 on lubricant 0-79-16, were originally scheduled for 250-hr duration. It will be noted that three of the extended duration tests were terminated prior to 250 hr. Two of these tests were terminated due to mechanical problems, as shown in the footnotes of Table 3. Test No. 17 using lubricant 0-72-8, was terminated after 150 hr operation in the earlier contract[1] due to the contract period expiration.

The results from the extended duration tests show that the increase in deposit ratings from the values presented for the 100-hr inspection ranged from 1.7 for 0-74-2 to 3.8 for 0-73-1. The overall average increase in deposit rating after the 100-hr inspection, for the extended duration tests was 2.4 which represents an average increase of approximately 13.5 percent. Although 0-73-1 appears to have provided the largest deposit rating increase of 23.8 percent, if one considers the average 100-hr deposit rating of 17.9 for 0-67-23 and 0-79-16, different batches of the same lubricant formulation, and compares this average with the average 250-hr deposit rating, 23.2, for 0-67-23 and 0-79-16, the largest deposit rating increase will be approximately 29.6 percent for this lubricant formulation. Further, when the test duration was extended to 350 hr, the deposit rating was further increased to 34.3, or an 91 percent increase over that shown for 100-hr operation. It should be mentioned that the deposit rating shown for lubricant 0-79-16, Test No. 26, may be high due to increases in the

iron content noted after approximately 270 hr operation and continuing through approximately 310 hr operation; and, also a significant increase in breather air pressure during the last 10 hours of operation which did not change when the simulator was cycled from 9120 rpm to 6000 rpm, and then back to 9120 rpm.

With respect to viscosity and neutralization number increases during the extended duration tests, lubricant 0-73-1 showed the largest viscosity increase with 17.1 percent, lubricant 0-74-2 the largest neutralization number increase with 2.4 mg KOH/g. Neither of these values approached the arbitrary limits set for test termination.

Problem Areas

Three problem areas have been encountered with the engine simulator during the last few tests using the Auto 1 test procedure.

1. It has been necessary to manually control the simulator shaft speed and the on-off control functions of the test-oil pressure pump during the last seven tests. This problem is believed to be due to a spurious electrical cross feed in the automated control circuits of these two items. Project completion time and an overall lack of sufficient maintenance money did not allow for tracing and repairing this problem.

2. One test, Test No. 33, was lost after only 17.5 hr operation due to power to the No. 5 area electrical heaters not being automatically reduced to zero during the one-hour soak-back period following the 17.5 hr operating period. This malfunction was traced to a sticking power supply controller and was corrected by replacing a diode and a fuse. No indication of a temperature problem was noted until the end of the soak-back period and the simulator would not start due to an indication of an overtemperature in the No. 5 area. It will be

necessary in the future to include a software program which will signal an overtemperature during the soak-back period.

3. It is suspected that during Test No. 34, the computer malfunctioned somewhere between 66 and 67.5 hr of operation, allowing the simulator to continue to run, and did not control or record the temperatures, or pressures during this period. It was discovered that the computer was not functioning correctly during the soak-back period. A service call by Hewlett-Packard maintenance personnel, requiring the replacement of a "CPU board" corrected the problem. However, an alarm system should be incorporated in the future to eliminate any suspicions of computer malfunction.

These problem areas should be corrected in the future when maintenance funds are available.

CONCLUSIONS

The automated engine simulator test facility, designed, installed, and operated at SwRI, is capable of closely simulating the critical temperature and oil flow variables experienced in a full-scale J57-29 turbine engine. The simulator, designated the AFAPL engine simulator, uses a No. 4-5 bearing compartment area of a J57-43 turbine engine modified to allow air pressurization and electrical heating of the area surrounding the oil-wetted section of the No. 4-5 bearing compartment area. The AFAPL engine simulator is designed to allow controlled air temperatures to be varied up to 850°F (454°C) and test oil tempeatures up to 450°F (232°C) to be used. A variable speed drive system, driving the simulator through the accessory drive gearbox, provides compressor shaft speeds up to 9,120 rpm.

A total of over 4,300 hr operation have been accumulated on the AFAPL engine simulator during the evaluation of 24 test lubricants. Approximately 1700 hr of this total have been run using the computer controlled mode (Auto 1 test procedure) of operation. Eight of the lubricants evaluated in the AFAPL engine simulator had previously been evaluated in the APL full-scale engine test. A comparison of the numerical deposit ratings obtained using the AFAPL engine simulator with those obtained from the No. 4-5 area of the full-scale engine shows good correlation, with a calculated correlation coefficient of 87.4 percent. Further, the data from 10 full-scale engine tests using seven different lubricants shows that the No. 4-5 area of the full-scale engine contributes an average of 23.2 percent of the total numerical engine deposit rating. Since good correlation is shown for the numerical ratings obtained from the engine simulator and the No. 4-5 area of the full-scale engine, multiplying a deposit rating obtained from the AFAPL engine simulator by the reciprocal of 0.232 provides a reasonable estimate of the total full-scale engine deposit rating for the same lubricant. The estimated total engine deposit ratings obtained in this manner did not provide the exact same relative

ranking of the lubricants which passes the APL full-scale engine test. However, the estimated total engine deposit ratings obtained from engine simulator ratings did estimate a passing deposit rating, less than 85, for each of the six lubricants which had passed the APL engine test. The estimated total engine deposit rating for the one lubricant which failed the APL engine test was 99.1 compared with a deposit rating of 97.3 from the engine test. In addition, one lubricant which was removed from the MIL-L-7808 QPL list in 1967, due to its depositon characteristics, provided an estimated total engine deposit rating of 105.2 when evaluated in the AFAPL engine simulator test. A numerical deposit rating from the APL engine test run in 1962 is not available for this lubricant; but the estimated deposit rating of 105.2 indicates that this lubricant would certainly fail the current APL engine test requirements.

Extended duration tests, up to 350 hr duration, were conducted with the AFAPL engine simulator using eight different lubricants to determine the effect of additional test time on the physical properties and the deposition characteristics of the lubricants, since full-scale engine data are not available for test periods beyond 100 hr. It was found that the 250-hr deposit rating increase, when compared with the 100-hr deposit rating, ranged from essentially no change for lubricant 0-72-13 to a maximum of 29.6 percent increase for different batches of 0-67-20. The 350-hr deposit rating for 0-79-16, another different batch of 0-67-20, indicated a 91 percent increase over that shown for 100-hr operation.

RECOMMENDATIONS

The following recommendations are believed to be justified based upon the information generated to date using the AFAPL engine simulator:

1. All candidate turbine engine lubricant formulations should be evaluated in duplicate simulator tests of 100-hr each prior to being considered for full-scale engine testing.

2. A minimum of one extended duration simulator test, perhaps extending to 500 hrs, should be conducted on each turbine engine lubricant being considered for inclusion in a Qualified Products List.

3. In order to obtain an increased return on the money invested in the automated engine simulator system, it is recommended that a second set of 4-5 area hardware be obtained and be used for a second engine simulator set-up. In this manner, one set of 4-5 area hardware could be run by the computer while the second set was being torn down, rated, cleaned and prepared for the next test by the technicians. In this manner, the utilization of the expensive computer control hardware and software systems of the engine simulator, as well as the technicians trained for the simulator operation would be significantly improved.

4. It is recommended that the problem areas of rpm control, oil pressure pump on-off control, and computer control malfunction alarm be corrected and added to the system when maintenance funds are available.

5. It should be emphasized that the use the AFAPL engine simulator is not limited to the evaluation of lubricants of specific interest to only the Air Force; but, could be used to evaluate lubricants of interest

to the Navy and Army equally well. Due to the flexibility of the engine simulator control system, changes can be made in the operating conditions of the simulator such that practically any reasonable change, to satisfy a specific requirement, can be incorporated if it is desired.

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